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Heat Flow and Gravity Interpretation Across the Rio Grande Rift in Southern New Mexico and West Texas

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Recent heat flow measurements at 10 separate localities in southern New Mexico and west Texas range from 0.9 to 3.6 HFU (1 HFU = 1×10^{-6} cal/cm^2 s). Radiogenic heat production determinations at eight of these localities range from 2.2 to 4.9 HGU (1 HGU = 1×10^{-13} cal/cm^3 s). When the heat flow measurements are reduced by the heat from bedrock radioactivity, the Rio Grande rift and immediately adjacent areas are characterized by very high reduced flux ($\geq$1.8 HFU), which contrasts strongly with 1.2- to 1.5-HFU values in bordering portions of the Basin and Range province and a 0.8-HFU value assumed for the southern Great Plains. Analyses of 2000 gravity observations in the Basin and Range province and the Great Plains reveal that a positive gravity ridge of about +30 mGal occurs along the Rio Grande rift in the Franklin and San Andres mountains and the Tularosa Valley. This relative gravity high can be caused by crustal thinning and/or shallow sills and dikes of mafic rocks in the crust under the rift. Gravity anomalies and a thin crust are compatible with a low-density upper mantle beneath most of the Basin and Range province. The new heat flow and radioactivity data indicate that the Basin and Range-Great Plains heat flow transition is marked by unusually high observed and reduced flux in the neighborhood of the Rio Grande rift. The combined thermal and gravity observations may be explained by shallow crustal intrusions, a hot abnormal upper mantle, and relative crustal thinning beneath the rift.

INTRODUCTION

The Rio Grande rift in southern New Mexico is an area of young basaltic volcanism and young extensional tectonics [*Chapin*, 1971; *Kelley*, 1952, 1956]. In addition to local geology, heat flow, magnetic time variation, and limited seismic data indicate that the rift marks a major change in crustal and upper mantle structure from the southern Great Plains to the Basin and Range province in western New Mexico [*Warren et al.*, 1969; *Roy et al.*, 1972; *Edwards et al.*, 1973; *Schmucker*, 1964, 1970; *Stuart et al.*, 1964; *Stewart and Pakiser*, 1962; *Smithson and Decker*, 1972]. This paper presents a geophysical interpretation of the rift and bordering areas based on new combined heat flow, radioactivity, and gravity observations in southern New Mexico and west Texas.

Figure 1 shows the areas of our investigation. The major physiographic provinces are after *Fenneman* [1946]. The outline of the Rio Grande rift follows the definition given by *Chapin* [1971] rather than that given by *Kelley* [1952, 1956].

GENERALIZED GEOLOGY

The Precambrian basement of southern New Mexico is covered with a sequence of sedimentary rocks ranging in age from Cambrian to Cretaceous. In the Caballo Mountains these sedimentary rocks are tightly folded and overturned to the northeast by Laramide deformation, and in the Franklin Mountains they are overturned to the northwest [*Harbour*, 1972]. Early to middle Tertiary granitic stocks were emplaced from Cornudas, Orogrande, and Las Cruces on the east to Silver City and Lordsburg on the west [*Kottlowski et al.*, 1969]. Widespread extrusion of basaltic, andesitic, and rhyolitic flows and tuffs occurred throughout the Tertiary. High-angle faulting began in the Miocene and continued through the Pleistocene [*Kelley and Silver*, 1952]. The area from the western margin of the Sacramento Mountains to southern Arizona has Basin and Range structure and topography. The horsts are composed of Precambrian, Paleozoic, and Mesozoic sedimentary rocks, Tertiary volcanic rocks, and granitic intrusives. They are partially buried by their own debris, because the grabens have filled with Tertiary sediments containing much volcanic material. The Rio Grande rift developed since the late Miocene. Although young volcanic rocks occur throughout southern New Mexico and west Texas, Quaternary basalts are scattered throughout the rift and extend northward from the Potrillo Mountains along the Rio Grande Valley to northern New Mexico [*Dane and Bachman*, 1965; *Kottlowski et al.*, 1969; *Hoffer*, 1969].

HEAT FLOW AND GRAVITY STUDIES

New heat flow and radioactivity data. Basic heat flow data and generalized geology at 10 heat flow stations in southern New Mexico and west Texas are summarized in Tables 1 and 2, respectively. Radioactivity data for eight of these sites are summarized in Table 3. The drill hole near Cornudas, New Mexico, was drilled by Harvard University for heat flow studies; all other holes were drilled by mining companies for exploration purposes. Values of thermal conductivity (C), uranium (U), thorium (Th), potassium (K), and heat production (A) are means of measuring core samples from each locality. *Roy et al.* [1972] have presented generalized maps and profiles of the terrain-corrected heat flow values (q_T) at nine of the localities; the terrain-corrected heat flow values and the measurements of conductivity, temperature, and terrain for these sites are also summarized by *Decker and Birch* [1974]. The rest of the data are new.

Thermal data were acquired and reduced by using equipment and techniques described by *Roy et al.* [1968*a*]; therefore readers are referred to their paper for details concerning the accuracy and precision of temperature and thermal conductivity measurements and the methods for calculating observed (q_{unc}) and terrain-corrected (q_T) heat flow values. Radioelement concentrations were determined by gamma ray counting at Rice University and the University of Wyoming (Table 3). The measurements of U, Th, and K by Rice are considered to be accurate to within ±5% [*Adams*, 1964], whereas those by Wyoming have estimated accuracies of ±20% for U, ±10% for Th, and ±5% for K [*Decker*, 1973].

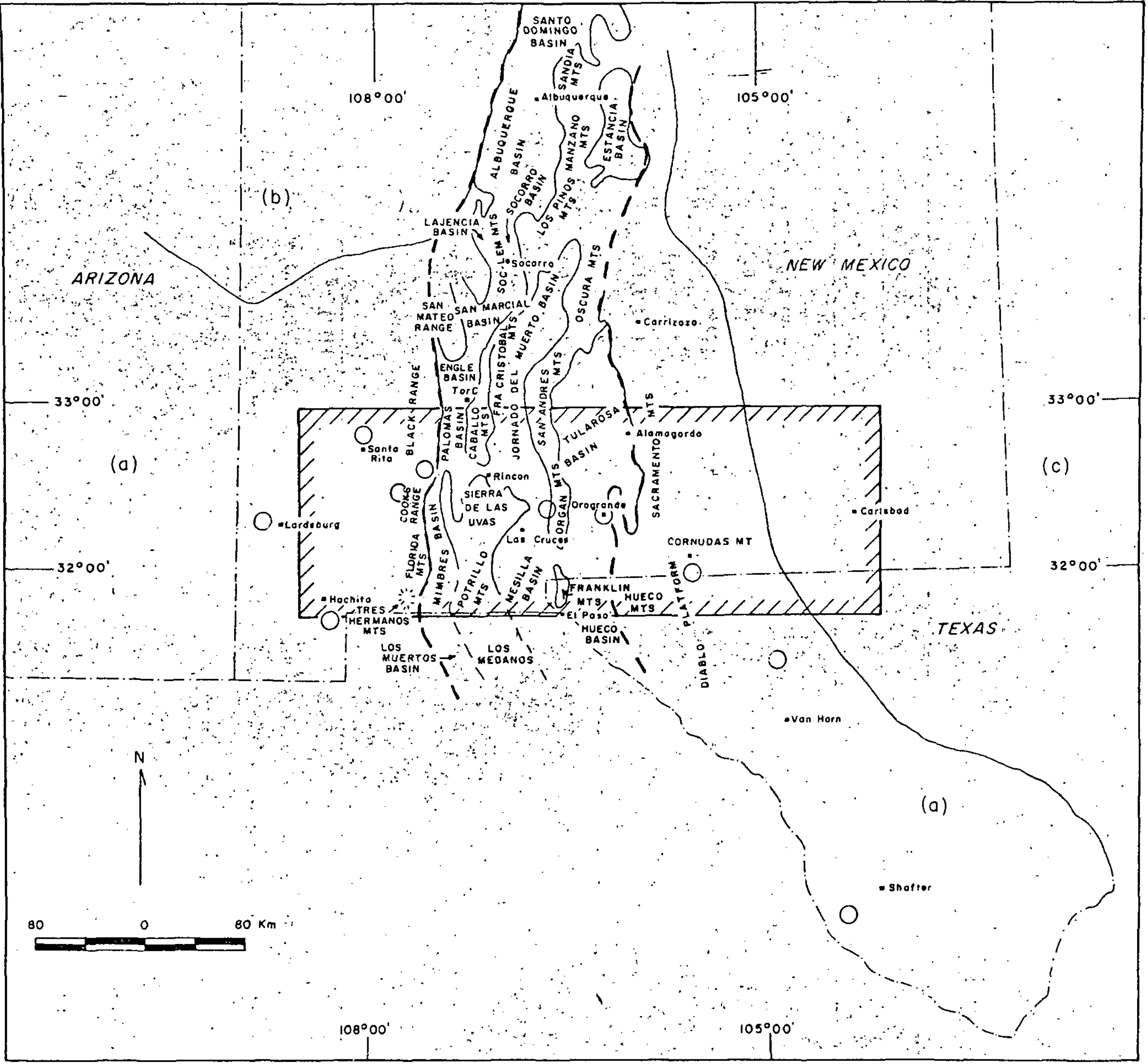

Fig. 1. Generalized map of areas investigated. Physiographic provinces are taken from *Fenneman* [1946]: *a* refers to Basin and Range province, *b* refers to the Colorado Plateau, and *c* refers to the Great Plains. The dashed line outlines the Rio Grande rift as defined by *Chapin* [1971]; all other localities, etc., are after *Chapin* [1971, Figure 2]. Large circles represent locations of new heat flow stations. The area covered by new gravity measurements is indicated by hatching.

Roy et al. [1968*a*] and *Decker* [1969] have reported heat flow values from drill holes near Hachita, Lordsburg, and Santa Rita, New Mexico. The best values of flux listed in Table 1 for these areas are the mean values of all currently available determinations. A best value is also listed for Shafter, Texas, where a shallow conductivity contrast may cause higher gradients and flux in the upper 600 m of the hole (Table 2).

The holes at Organ and Orogrande, New Mexico, penetrated Laramide stocks that are bordered by 2- to 3-km-deep basins containing alluvium, limestones, dolomites, sandstones, and shales of variable thicknesses [e.g., *Kottlowski*, 1963]. Although best values of flux have not been determined for these areas, the effects of possible sources of error have been estimated, and ranges of refraction-corrected heat flow are listed for each locality (Table 1). For both locations the minimum values were selected from the results of several calculations based on two- and three-dimensional models of the local geologic structure and assumed thermal conductivities [after *Birch*, 1942; *Clark*, 1966] for the sedimentary basins. More detailed calculations will require accurate knowledge of the local structure and conductivity distributions, but the ranges of flux are reasonable bounds for the undistorted heat flow near these holes.

A measure of the reliability of the heat flow values at all remaining stations is provided by the quantity of data used for calculations. In general, the determination of flux is less reliable if a small number of conductivity samples or a short interval of hole was used for calculations (e.g., Cooks Peak, New Mexico). It is difficult to be more specific without more data near some of these stations.

Reduced heat flow values (q_R in Table 3) were calculated according to the definition given by *Roy et al.* [1972]. Briefly, the topographically corrected, best, or refraction-corrected values at each station were reduced by a value of flux equal to AH,

TABLE 1. Summary of Basic Heat Flow Data for Drill Holes

Locality and Symbol (Figure 2)	Location	Collar Elevation, m	Depth Range, m	C, mcal/cm s °C	No. of Conductivity Samples	Gradient, °C/km	Heat Flow, HFU		Method†
							q_{unc}	q_T*	
New Mexico									
Cornudas (CM)	32°01'N, 105°29'W	1410	320-370	9.6 ± 0.4	33	22.0 ± 0.5	2.04 ± 0.04	2.02	RI
							2.0§		
Cooks Peak (CP)	32°32'N, 107°41'W	1634	130-205	9.8 ± 1.0	6	38.3 ± 0.4	3.8 ± 0.4	3.6	GR
							3.6§		
Hachita (HC)	31°51'N, 108°18'W	1443	120-280	7.0 ± 0.1	11	33.5 ± 0.3	2.34 ± 0.06	2.32	RI
							2.4§		
Lake Valley (LV)	32°43'N, 107°35'W	1695	120-365	6.3 ± 0.2	57	41.1 ± 0.3	2.58 ± 0.10	2.59	I
							2.6§		
Lordsburg (LR)	32°20'N, 108°47'W	1357	130-200	5.10 ± 0.09	6	33.8 ± 0.2	1.72 ± 0.04	1.78	GR
							1.7§		
Organ (OG)	32°27'N, 106°36'W	1558	40-190	9.5 ± 0.3	32	29.1 ± 0.2	2.78 ± 0.10	2.76	GR
							2.1-2.8¶		
Orogrande (ORO)	32°24'N, 106°07'W	1366	300-360	7.3 ± 0.2	41	42.8 ± 0.4	2.95 ± 0.06	3.08	RI
							2.5-3.1¶		
Santa Rita (SR)	32°48'N, 108°04'W	1924	100-300	6.6 ± 0.1	39	25.10 ± 0.05	1.65 ± 0.03	1.58	GR
							1.8§		
Texas									
Shafter (SH)	29°48'N, 104°24'W	1250	180-560	8.2 ± 0.1	69	24.8 ± 0.1	2.03 ± 0.05	2.06	GR
			560-620	9.1 ± 0.5	11	21.0 ± 0.1	1.92 ± 0.12	1.93	GR
			620-880	8.9 ± 0.2	49	16.91 ± 0.08	1.51 ± 0.04	1.51	GR
							1.5§		
Van Horn (VH)	31°27'N, 104°53'W	1319	330-400	6.8 ± 0.1	8	15.05 ± 0.09	1.03 ± 0.02	0.99	GR
							1.0§		

The ± refers to standard errors.

*With the exception of Cooks Peak, terrain-corrected flux (q_T) is presented in a general way by *Roy et al.* [1972]; the basic data and principal elements of each heat flow calculation are also given by *Decker and Birch* [1974].

†Procedure used to calculate uncorrected (q_{unc}) heat flow; symbology and procedures are exactly as outlined by *Roy et al.* [1968*a*].

§Best value.

¶Range of refraction-corrected values.

TABLE 2. Generalized Geology at Heat Flow Stations

Location	Description
Cornudas	Dolomitic limestones with thin layers of shale and one rhyolite porphyry sill. Local dip <10°.
Cooks Peak	Altered andesite breccia.
Hachita	Rhyolite porphyry.
Lake Valley	Rhyolite, 0-240 m; limestones, 240-284 m; rhyolite, 284-305 m; limestones with some shale, 305-365 m. Radioactivity samples of core of granitic gneiss in the basement below.
Lordsburg	Intrusive basalt with minor felsic units.
Organ	Quartz monzonite.
Orogrande	Quartz monzonite with some magnetite-rich limestones. Radioactivity samples of quartz monzonite only.
Santa Rita	Granodiorite.
Shafter	Altered rhyolite, latite, and felsite porphyry near surface. Monzonite porphyry below. Conductivity and radioactivity samples in monzonite porphyry. Hole penetrates a plug or stock bordered by limestones and siltstones.
Van Horn	Monzonite porphyry.

where A is the local radiogenic heat production and H is taken to be 10 km. A 10-km value was assumed for H because it agrees with the slope (9.4 ± 1 km) of the Basin and Range heat flow–heat production line [*Roy et al.*, 1968*b*] and because a similar value (~10 km) was used to calculate previously published reduced heat flow values in southern New Mexico [*Roy et al.*, 1972].

For brevity throughout the remainder of this paper the units of heat flow, 10^{-6} cal/cm^2 s, will be abbreviated to HFU, and the units of radiogenic heat production, 10^{-13} cal/cm^3 s, to HGU. The term 'unreduced' will be associated with the terrain-corrected, best, or previously published heat flow values that have not been reduced by the flux from local bedrock radioactivity according to the procedure described above.

Regional geothermal data: Both previously calculated reduced heat flow values in southern New Mexico are in the range 1.3–1.5 HFU, values typical of those found by *Roy et al.* [1972] in the Great Basin to the west. Data now available indicate that the unreduced and reduced heat flow in the vicinity of the Rio Grande rift are anomalously high with respect to both the Basin and Range and the Great Plains.

Figure 2 shows all the previously published geothermal measurements in southern New Mexico and west Texas together with the present results (Tables 1 and 3). A striking feature of the map is the region of very high unreduced heat flow (2.4–3.6 HFU) defined by the new measurements from Orogrande to Hachita. On the basis of the terrain-corrected data at these sites, the reduced flux in this anomalous zone ranges from 2.0 to 3.4 HFU. The reduced flux in this area would range from 1.8 to 3.4 HFU after corrections for refraction at our sites near Organ and Orogrande. West and north of these points the new data at Lordsburg and Santa Rita confirm typical Basin and Range unreduced heat flows of 1.7 and 1.8 HFU and significantly lower reduced values of 1.5 and 1.4 HFU. The new combined data at Shafter, Texas, also indicate significantly lower unreduced and reduced flux (1.5 and 1.2 HFU, respectively) in the Basin and Range south and east of Orogrande.

Warren et al. [1969] reported an observed heat flow of 2.24 HFU in a small diorite stock about 10 km north of our site

TABLE 3. Summary of Radioactivity and Reduced Heat Flow

Locality	Rock Type	No. of Radioactivity Samples	U, ppm	Th, ppm	K, %	Heat Production A, 10^{-13} cal/cm^3 s	Reduced heat flow q_R, 10^{-6} cal/cm^2 s
New Mexico							
Cooks Peak	Andesite (W)	15	0.98 ± 0.03	6.82 ± 0.04	2.93 ± 0.01	2.3	3.4
Hachita	Rhyolite porphyry (W)	3	2.7 ± 0.2	11.9 ± 1.6	3.5 ± 0.4	4.3	2.0
Lake Valley	Granite gneiss (R)	8	2.0 ± 0.4	17.5 ± 2.8	3.1 ± 0.6	4.7	2.1
Lordsburg	Basalt (W)	14	1.4 ± 0.1	5.6 ± 0.2	2.1 ± 0.3	2.2	1.5
Organ	Quartz monzonite (R)	23	2.5 ± 0.4	9.1 ± 0.9	1.3 ± 0.2	3.3	1.8-2.5
Orogrande	Quartz monzonite (R)	10	3.5 ± 0.2	12.3 ± 0.4	3.6 ± 0.2	4.9	2.0-2.6
Santa Rita	Granodiorite (W)	18	1.7 ± 0.3	10.2 ± 0.4	6.4 ± 0.3	4.1	1.4
Texas							
Shafter	Monzonite porphyry (W)	12	1.5 ± 0.1	8.5 ± 0.3	5.5 ± 0.3	3.5	1.2

W, radioactivity measurement made by University of Wyoming; R, radioactivity measurement made by Rice University. The ± refers to standard errors.

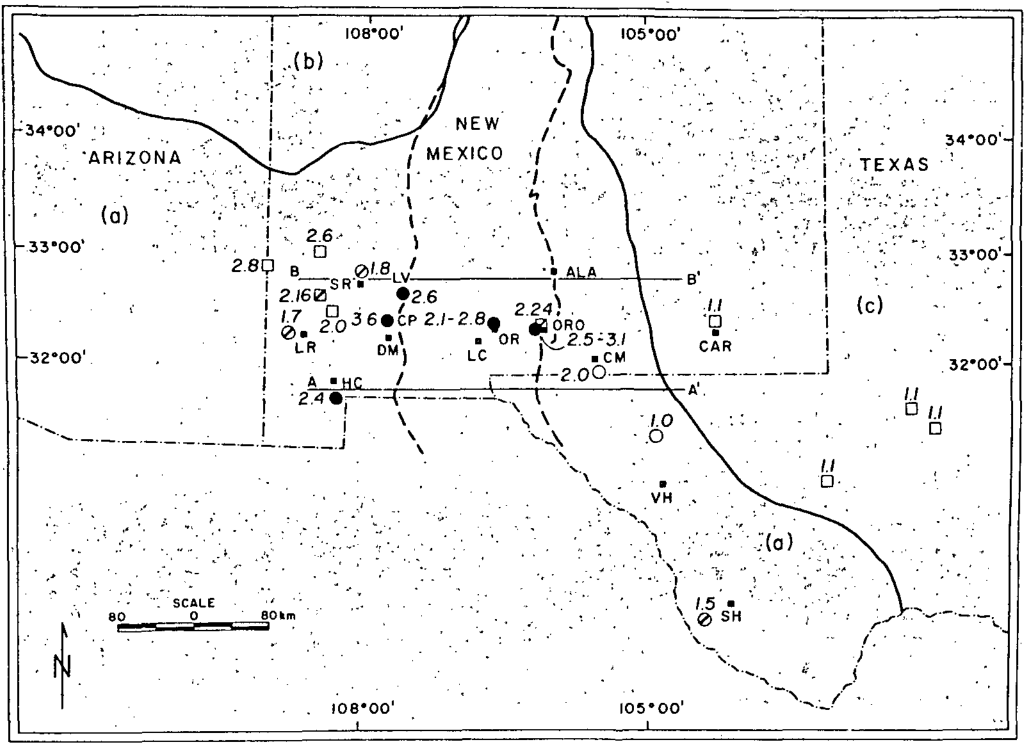

Fig. 2. Heat flow measurements in southern New Mexico and west Texas. Unreduced heat flow values are shown next to each locality. Units are HFU. Open squares represent locations of previously published unreduced values; open circles represent locations of previously unpublished unreduced values; slashed squares locate sites where previously published reduced values are in the range 1.4–1.5 HFU; slashed circles locate sites where previously unpublished reduced values are in the range 1.2–1.5 HFU; and solid circles locate sites where previously unpublished reduced values are in the range 1.8–3.4 HFU. Lines AA′ and BB′ represent the locations of gravity profiles through the area (see Figures 3 and 4). Physiographic provinces are after *Fenneman* [1946]: *a* refers to the Basin and Range province, *b* refers to the Colorado Plateau, and *c* refers to the Great Plains. The dashed line outlines the southern Rio Grande rift as defined by *Chapin* [1971]. Heat flow data are from *Roy et al.* [1968*a*, *b*], *Warren et al.* [1969], *Decker* [1969], *Herrin and Clark* [1956], and Tables 1 and 3 of this paper. Abbreviations for localities are DM, Deming; LC, Las Cruces; CAR, Carlsbad; and ALA, Alamogordo. Other abbreviations are given in Table 1.

near Orogrande. On the basis of the 6.7-HGU heat generation of the diorite given by *Roy et al.* [1968*b*], the reduced flux at this site would be 1.5 HFU. However, the unreduced value obtained by Warren et al. also could be different from the actual regional flux due to conductivity and radioactivity contrasts between the diorite and the limestones and dolomitic limestones in bordering basins [e.g., *Kottlowski,* 1963]. For example, calculations for elliptically shaped basins indicate that the observed flux in the diorite, with $C = 5.9$ [*Warren et al.,* 1969], could be 10% lower than the true regional heat flow if the bordering limestones have conductivities approaching those ($C = 7.3$–7.5) of similar units near Santa Rita [*Decker,* 1969]. Since the heat production of the diorite probably is greater than that of the bordering sediments, additional corrections for finite size of the stock could increase the unreduced flux by another 5–10% [e.g., *Birch et al.,* 1968; *Lachenbruch,* 1968]. If a correction of +15% for these effects is applied at this site, the reduced flux is 1.8 HFU, a high value comparable to that (2.0 HFU) obtained after corrections for refraction at our site just to the south.

As is evident in Figure 2, all the sites in the anomalous region bounded by Orogrande and Hachita are in or near the Rio Grande rift as defined by *Chapin* [1971]. On the basis of our best data at Lake Valley and Hachita and the refraction-corrected data at Organ and Orogrande, the reduced heat flow in the rift area is +0.4–0.7 HFU higher than the values in bordering portions of the Basin and Range. Relative to the Great Plains the reduced anomaly in the rift ranges from +1.0 to 1.7 HFU, if the 1.0- to 1.1-HFU observed values in the plains are taken to imply a reduced heat flow of 0.8 HFU. The reduced heat flow anomaly in the rift near Cooks Peak would be 2.0 and 2.6 HFU relative to the Basin and Range and the Great Plains, respectively. However, our unreduced value here is less reliable owing to limited conductivity data (Table 1), and it might be risky to assume that the altered andesite extends to great depth.

Gravity data. As is evident from the large uncontoured areas between Deming and Carlsbad on the gravity map of the United States [*Woollard and Joesting,* 1964], gravity measurements in southern New Mexico and west Texas are too widely separated to allow reliable modeling of the rift area. We have therefore measured 2000 additional gravity stations to fill in obvious gaps and obtain a more reliable picture of the gravity field. Two profiles (Figures 3 and 4) are presented to illustrate the anomalies. The stations were distributed over the entire area, and the profiles are based on contoured values. Terrain corrections have not been applied to the profiles because they would be less than 0.2 mGal at most stations and would not affect the anomalies.

Free-air anomalies show the usual correlation with topography and average −9 mGal along the two profiles (Figures 3 and 4). This small mean free-air value together with the near-zero values on *Woollard's* [1966] widely separated regional profiles suggests that the area is in isostatic equilibrium. Therefore the theory of isostasy can be used as a constraint for modeling.

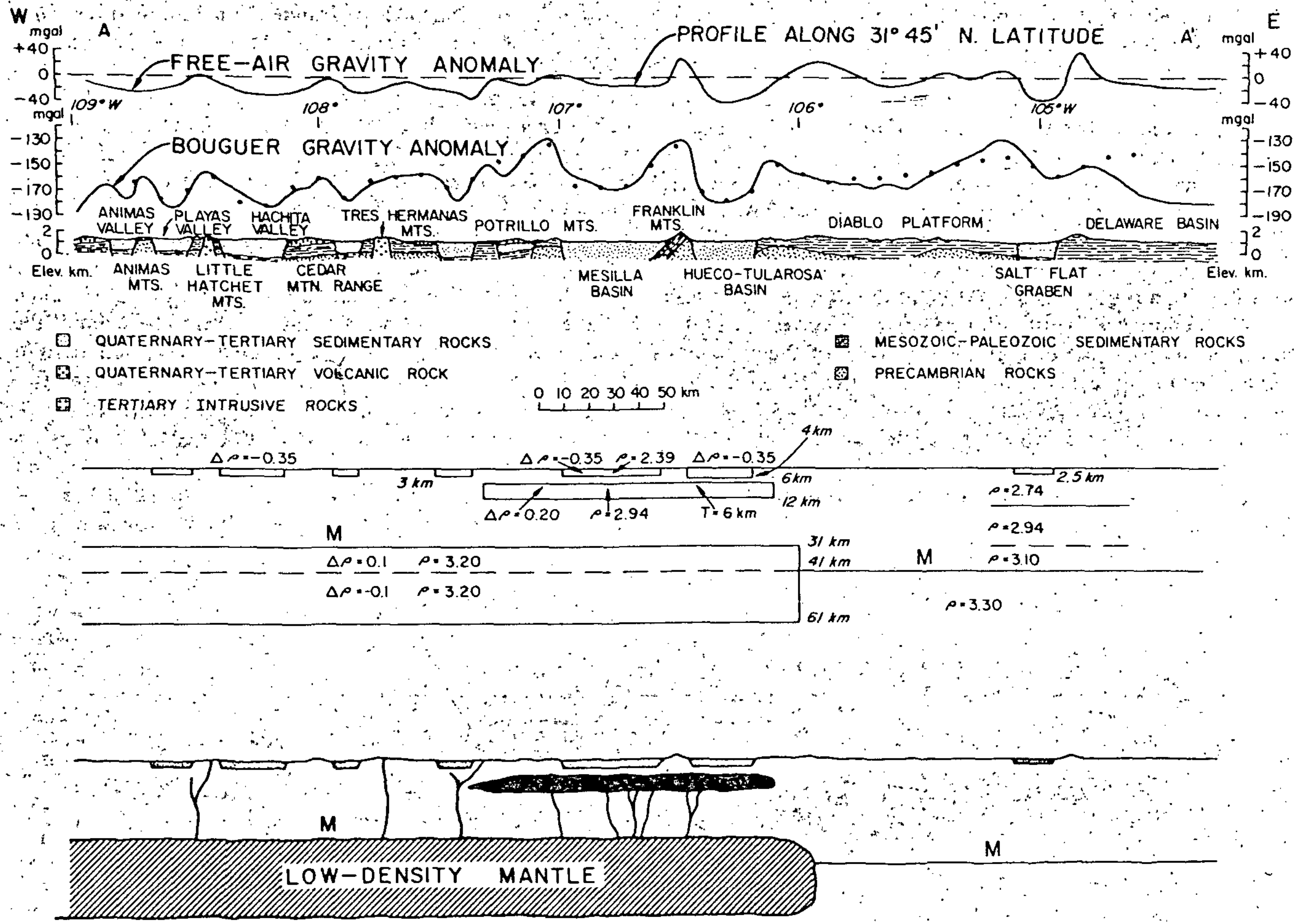

Fig. 3. Free-air gravity anomaly profile, Bouguer gravity anomaly profile, geologic cross section, gravity model, and geologic interpretation along latitude 31°45'N (line AA' in Figure 2). The interpretation is a shallow basalt slab under the Rio Grande–Tularosa Valley area and a pillow of low-density mantle under the Basin and Range province. The Moho is designated by M. Density (ρ) units are grams per cubic centimeter. Dots are calculated gravity values. The thickness of basalt slab is T.

The general features of the Bouguer anomaly profiles are relatively high gravity values over uplifts and low gravity values over the intervening basins (Figures 3 and 4). Like similar Bouguer profiles over the Rio Grande trough to the north [*Joesting et al.*, 1961; *Sanford*, 1968] and those across deep sediment-filled grabens in the Great Basin in Nevada and Utah [*Thompson*, 1959; *Cook et al.*, 1967], these gravity anomalies further confirm Basin and Range structure in southern New Mexico.

A Bouguer gravity high occurs just east of the Rio Grande River along the San Andres and Franklin mountains (Figures 3 and 4) and forms the major gravity axis through the rift area. The Tularosa Basin is a distinct gravity low in comparison with the San Andres Mountains just to the west; the decrease of Bouguer gravity takes place over a lateral distance of 10–15 km and approaches −30 mGal (Figure 3). The Mesilla Basin west of the Franklin Mountains is similarly a marked gravity low (Figure 4). Further to the east the Bouguer relief from the Tularosa Basin to the Sacramento Mountains and Great Plains is small (Figure 3). The regional Bouguer anomaly decreases by about 20 mGal from the Great Plains to the Basin and Range.

INTERPRETATIONS

The foregoing tables and figures summarize eight new values of heat production, one new value of flux, and 2000 new measurements of gravity in southern New Mexico and west Texas. We call attention here to some interpretations allowed by the combined heat flow and gravity studies and elaborate on their correlation with other geological and geophysical results.

Heat flow and subsurface temperatures. Steady state temperature curves for most of the Basin and Range province have been presented by *Warren et al.* [1969], *Blackwell* [1971], *Roy et al.* [1972], and *Lachenbruch* [1970]. For a surface flux of about 2.0 HFU and the melting curve of slightly wet peridotite, their curves imply that the top of a zone of partial melting could occur at 50- to 70-km depths in the upper mantle [e.g., *Roy et al.*, 1972]. Because the Rio Grande rift in southern New Mexico appears to be characterized by unusually high unreduced and reduced flux, higher temperatures could occur at the same depths in the mantle. For example, calculations based on models with a 1.8-HFU mantle heat flow in comparison with a 1.4-HFU mantle heat flow lead to 1100°–1300°C temperatures at depths of 30–45 km and imply partial melting in the lower crust and upper mantle beneath the rift (Figure 5). Higher upper mantle temperatures in the rift are consistent with an upwarping of higher electrical conductivity in the upper mantle between Lordsburg and Cornudas, New Mexico, on the basis of transient magnetic variation studies [*Schmucker*, 1964, 1970]. High temperatures (1200°C) and high electrical conductivity in the upper mantle, in turn, correlate with widespread late Tertiary to Quaternary basaltic volcanism in the rift [*Dane and Bachman,* 1965; *Kottlowski et al.,* 1969]. *Schmucker* [1970] also notes the presence of young volcanic units in the rift but places his high electrical conductivity anomaly at a minimum depth of 100 km beneath Las Cruces and Cornudas.

The model used above has steady heat sources in the lower crust and upper mantle to explain increased heat flow in the rift. However, because the rift is an area of late Tertiary to Quaternary volcanism and extensional tectonics, part of the heat flow high could possibly be due to the transient effects of fairly recent crustal intrusions or penetrative convection in the upper mantle. The use of multiple intrusions in the crust and upper mantle to explain the anomaly also might reduce possibilities for large amounts of crustal anatexis; *Roy and Blackwell* [1966] have postulated cyclic disturbances at the crust-mantle boundary to account for high flux in the Great Basin in Nevada, without implying extensive melting of the lower crust.

The Basin and Range–Rio Grande rift heat flow transitions occur over short lateral distances; the extreme examples are the changes from a 1.4-HFU reduced flux at Santa Rita to reduced values of 2.1 and 3.4 HFU at Lake Valley and Cooks Peak, respectively, about 60 km away. From Orogrande, with an unreduced heat flow of 2.5–3.1 HFU, to Cornudas, with 2.0 HFU, the horizontal distance is about 90 km. Without concomitant evidence for greater thicknesses or higher values of bedrock radioactivity in the rift, models that employ the transient effects of recent crustal or upper mantle intrusions are preferred to explain the sharp boundaries of the anomaly. But these observations would not by themselves imply the presence of transient heat sources, as does the combination of unusually high flux and late Tertiary volcanism in the rift.

Interpretations from gravity. There are at least three noteworthy features of the gravity data: (1) the Bouguer anomaly relief on the basement between the High Plains and the Basin and Range is small, ranging up to 20 mGal after adjustments for sediment thickness using the basement map of

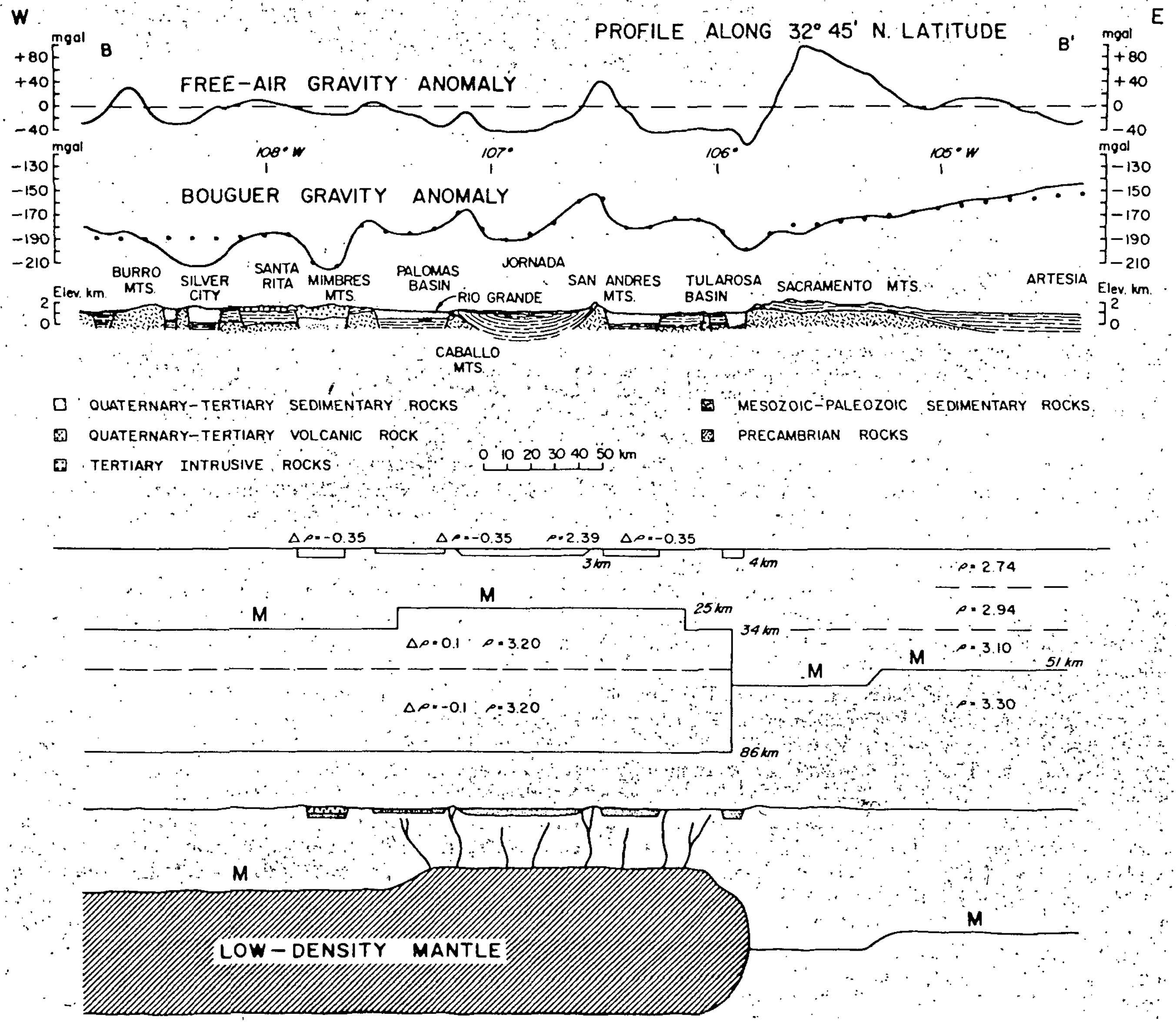

Fig. 4. Free-air gravity anomaly profile, Bouguer gravity anomaly profile, geologic cross section, gravity model, and geologic interpretation along latitude 32°45′N (line BB′ in Figure 2). An alternate interpretation is a 7-km upwarp at the crust-mantle interface and a low-density pillow in the upper mantle. The Moho is designated by M. Density (ρ) units are grams per cubic centimeter. Dots are calculated gravity values.

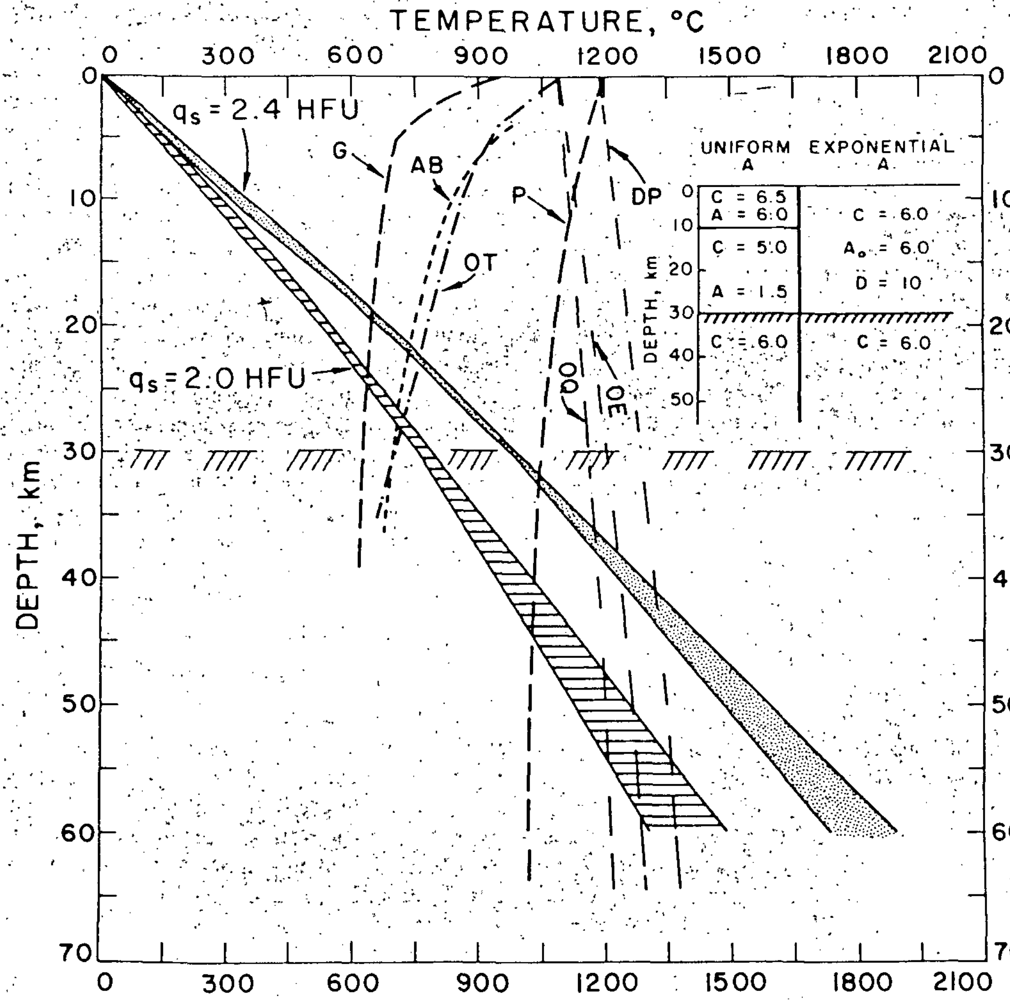

Fig. 5. Steady state temperatures as functions of depth beneath the areas investigated. Temperatures are calculated for models having crustal layers with uniform radioactivity [after *Roy et al.*, 1968*b*] and crustal radioactivity that decreases with depth according to $A(x) = A_0e^{-x/D}$, where x is depth, A_0 is the heat production at $x = 0$, and D is the logarithmic decrement [after *Lachenbruch*, 1968]. The horizontally lined area represents the range of temperatures calculated by using uniform (lower bound) and exponentially decreasing (upper bound) crustal radioactivity and an average surface flux (q_s) of 2.0 HFU for most of the Basin and Range province. The dotted area represents the range of temperatures calculated by using exactly similar crustal models and a surface flux (q_s) of 2.4 HFU in the southern Rio Grande rift. The base of the crust is indicated by hatching. Solidus curves in the presence of excess water are after *Wyllie* [1971], *Lambert and Wyllie* [1972], and *Yoder and Tilley* [1962]: G is granodiorite, P is peridotite, AB is alkaline basalt, and OT is olivine tholeiite. Dry solidus curves are after *Lambert and Wyllie* [1972]: OQ is olivine tholeiite to quartz eclogite at high pressures, OE is olivine tholeiite to olivine eclogite at high pressures, and DP is peridotite. The dry peridotite curve is the upper bound for all peridotite curves summarized by *Lambert and Wyllie* [1972]. See Tables 1 and 3 for units.

the United States [*Bayley and Muehlberger*, 1968]; (2) the −9-mGal mean free-air value suggests that areas investigated are in isostatic equilibrium; and (3) a Bouguer anomaly of about +30 mGal occurs in the Rio Grande rift along the Franklin and San Andres mountains. Inasmuch as the positive anomaly in the rift covers an area at least 60 km long, it is not likely to be caused by the limited exposures of dense Precambrian mica schist and amphibolite in the northern San Andres Mountains. Also, most of the basement rocks in this area are described as granitic [*Foster and Stipp*, 1961; *Harbour*, 1972]. This does not mean that the effect of near-surface changes of density can be ignored, because in places the gravity is dominated by contrasts between sediments and bordering crystalline rocks. Two good examples occur east of the Franklin and San Andres mountains, where interpretations of gravity and electrical measurements in adjacent portions of the Tularosa Basin indicate that the underlying sediments are 2 to 3 km thick [*Mattick*, 1967; *Zohdy*, 1969; *Zohdy et al.*, 1969]. In these areas a density contrast of 0.35 g/cm³ [after *Mattick*, 1967] between the sediments and the crystalline rocks in the mountains accounts for the Bouguer relief.

The preceding arguments indicate that the masses responsible for the relative Bouguer high in the rift and the small decrease of Bouguer gravity from the plains to the Basin and Range must be sought at depth. However, the gravity data do not permit unique decisions, and other control must be used in modeling. This control is provided by regional seismic data showing that a major change in crustal thickness occurs between the plains and southwestern New Mexico [*Stewart and Pakiser*, 1962; *Stuart et al.*, 1964].

Figures 3 and 4 show our preferred interpretations of gravity and seismic data along the two profiles. Gravity models were calculated on the basis of the two-dimensional program of *Talwani et al.* [1959], by using density-velocity data developed by *Birch* [1960, 1961] and C. Drake as reported by *Grant and West* [1965, Figure 7-7, p. 200]. A striking feature of each model is the low-density 'pillow' of upper mantle beneath the Basin and Range province. These low-density layers of upper mantle are required by the large changes of crustal thickness across the rift that do not produce corresponding large changes in the regional Bouguer anomalies. The extreme example would occur along latitude 32°45'N (Figure 4), where the 17- to 20-km decrease of crustal thickness between Carlsbad and southwestern New Mexico would cause an increase of Bouguer gravity of 200 mGal in the Basin and Range unless the upper mantle density decreases to the west. From the Diablo Platform to southwestern New Mexico (Figure 3) the decrease in crustal thickness is about 10 km, and the Bouguer anomalies in the Basin and Range would increase by 100 mGal without a concomitant density decrease in the upper mantle. The theory of isostasy also requires that the upper mantle beneath a thinner crust in the Basin and Range have a density lower than normal, as is indicated by a single determination of low P_n velocity (7.9 km/s) in southwestern New Mexico [*Stuart et al.*, 1964].

The low-density layers of upper mantle extend to different depths beneath the Basin and Range along the two profiles; the depth range is 34–86 km at latitude 32°45'N and 31–61 km at latitude 31°45'N (Figures 3 and 4). Different as well as finite vertical thicknesses of the low-density layers are needed to insure isostatic equilibrium of the contrasting crustal sections. These distributions of mass also explain the small changes in Bouguer gravity from the Basin and Range province to the Great Plains.

A 2- to 3-km-deep density contrast of 0.35 g/cm³ between juxtaposed crystalline rocks and low-density sediments would produce the Bouguer relief (−30 mGal) from the San Andres and Franklin mountains to the Tularosa and Hueco-Tularosa basins. Cenozoic sediments in the basins associated with rifting are 2 to 3 km thick (Figures 3 and 4). If the negative effect of 3 km of sediments is removed from the profiles across the basins, the Bouguer gravity over them is increased by 30 mGal. The positive gravity ridge in the rift would then be much broader, and Bouguer anomalies over these basins would be much more positive than those in the Sacramento Mountains and the Diablo Platform to the east. Although anomalies over the Sacramento Mountains and the Diablo Platform could be more negative owing to large buried granitic intrusions, another interpretation that would explain a relative Bouguer high over the basins is that they are underlain by large tabular bodies of high-density units as depicted in Figure 3. Such a mass could represent crustal intrusions of late Tertiary basalt and provide a transient heat source for anomalous flux in the rift. This interpretation is further supported by the widespread occurrence of Quaternary basalts along the trend of the rift [*Dane and Bachman*, 1965] and the evidence that numerous sediment-filled depressions seem to be underlain by mafic rocks [*Thompson and Talwani*, 1964; *Woollard*, 1969].

Bouguer anomalies in southern New Mexico generally decrease northward, corresponding to an increase in average elevation (Figures 3 and 4). Near the center of the profile at 32°45'N the Rio Grande River–Tularosa Basin area forms a relative topographic depression (Figure 4). The gravity model in Figure 4 reflects the lower Bouguer anomalies and higher elevations outside the rift by showing the Moho beneath bordering portions of the Basin and Range to be about 3 km deeper than the Moho in extreme southwestern New Mexico. To explain the topographic depression and Bouguer high in the Rio Grande River–Tularosa Basin area, however, a 9-km-thick upwarp of the mantle in the rift zone is proposed (Figure 4). This relative thinning of the crust could represent a diapiric intrusion of hot mantle into the rift zone and constitute a deeper time-dependent source for the reduced heat flow anomaly. In the real situation the thermal anomaly in the rift could be caused by shallow crustal intrusions (Figure 3), crustal attenuation (Figure 4), or a combination of both. It is not possible to resolve the models proposed in Figures 3 and 4 without more detailed data on shallow geologic structure and the surface and reduced heat flow variations in the rift; therefore these alternative interpretations are presented.

The models in Figures 3 and 4 have low-density and low-velocity zones reaching the base of the crust in the rift and the Basin and Range province. The assumption that a low-velocity zone extends up to the base of the crust implies a large degree of melting in the lower crust. Another interpretation that would be consistent with the thermal, gravity, and seismic data is that a thin layer (5–10 km) of higher-density unmelted material occurs between the crust and low-velocity zone. Such a layer would not be resolved gravimetrically if its gravity effect were counterbalanced by that of a low-density zone beneath it. The presence of such a layer would greatly reduce possibilities for extensive melting in the lower crust.

CONCLUDING REMARKS

This study is the first to show that the Rio Grande rift area in southern New Mexico is a zone of unusually high unreduced and reduced heat flow, which contrasts strongly with lower values in the Basin and Range high heat flow province as well as with normal flux in the High Plains. The new gravity measurements show that a Bouguer gravity high of about 30 mGal also occurs in the rift area and that the Bouguer relief from the Great Plains to the Basin and Range is small. These observations coupled with seismic evidence for contrasting crustal thicknesses in the Great Plains and Basin and Range provide the first geophysical evidence for mafic crustal intrusions, a low-density hot upper mantle, crustal attenuation, or a combination of all these phenomena in the rift zone. Although significant Bouguer anomalies occur elsewhere in the eastern part of the Basin and Range, most are caused by density contrasts between juxtaposed sedimentary basins and uplifts, and no single basin is gravimetrically more prominent than another. The gravity measurements therefore indicate that the rift could well be composed of a number of basins (e.g., Mesilla, Tularosa, Palomas) as defined by *Chapin* [1971]. *Chapin* [1971] also presents geological evidence for a local thinning of the crust beneath the rift zone. Because a 7- to 10-km upwarping of the Moho also would explain the Bouguer gravity high in the rift, our study establishes a geophysical base for this interpretation.

The sources responsible for the very high heat flow in the rift area must be in the crust or upper mantle because of the sharp boundaries of the anomaly. Unless radioactivity increases with depth or a thin lid of unmelted mantle occurs at the base of the crust, steady state interpretations of the heat flow anomaly in the rift imply a large degree of melting of the lower crust and upper mantle (Figure 5). However, the new data do not indicate increased bedrock radioactivity in the rift, and a thin lid of normal upper mantle is not resolvable with existing gravity and seismic data. Therefore models that employ the transient effects of late Tertiary mafic intrusions in and below a thinner crust are preferred to account for the anomaly. Such models, in turn, would explain the Bouguer gravity high and be consistent with the widespread occurrence of Quaternary basalts in the rift zone. Three other lines of evidence are considered consistent with these conclusions: (1) *Lipman* [1969] has shown that fractionation at shallow depths (15–20 km) beneath a thinner crust would produce the uncontaminated tholeiitic basalts in the rift in northern New Mexico and southern Colorado; (2) *Kudo et al.* [1971] propose that contaminated tholeiitic basalts found within the rift fractionated at shallow depths in the crust; and (3) thinner crust or mafic rocks at shallow depths have been proposed for a number of grabens of different ages [*Girdler*, 1964; *Cook*, 1969; *Mueller et al.*, 1969; *Ramberg and Smithson*, 1971; *Searle*, 1970; *Searle and Gouin*, 1972]. However, basalts found in the rift in southern New Mexico range from the alkali-olivine type in the Potrillo Mountains to olivine tholeiities in the Carizozo Mountains [*Renault*, 1970], fractionation at 50- to 60-km depths in the mantle thus being suggested. Perhaps the present heat flow and gravity highs in this portion of the rift are the result of younger penetrative convection to shallower depths in the lower crust and upper mantle.

The new gravity and seismic models for deep structure along the Great Plains–Basin and Range transition involve a change from a thick stable crust to a thinner crust underlain by low-density upper mantle coupled with crustal attenuation and/or crustal intrusions of mafic rock along the Rio Grande rift. Whether an upwarping of the Moho or high-density crustal intrusions are used to explain the Bouguer high in the rift, a low-density upper mantle must be present under the Basin and Range to reconcile the large changes of crustal thicknesses across the rift and the small Bouguer relief in the east-west directions. Because the Basin and Range is a zone of above-normal unreduced and reduced heat flow, large portions of this low-density mantle could be partially molten [*Roy et al.*, 1972; *Lachenbruch*, 1970]. If substantial amounts of partially molten mantle material migrated upward and also penetrated the crust in the rift during late Tertiary time, the unusually high flux and crustal distention could be achieved without massive amounts of anatexis. This does not mean that the injected mantle material would produce anomalously high gravity in the rift; for example, molten basaltic magma (for which there is evidence) that was recently intruded into the crust could have such a low density [*Bottinga and Weill*, 1970] that it would not cause large Bouguer anomalies.

The conclusions raise questions regarding the relation between heat flow and geomagnetic deep sounding in southern New Mexico and west Texas. From the data presented, mantle heat flow increases sharply in the region of transition from the Great Plains to the eastern part of the Basin and Range, followed by abnormally high unreduced and reduced flux in the rift immediately to the west. To a first approximation the anomalous flux in the rift area is consistent with an upwarping of high electrical conductivity and temperatures in the mantle based on the long-period magnetic variation studies of *Schmucker* [1964, 1970]. However, *Schmucker* [1970] places the electrical conductivity and temperature anomaly at a minimum depth of 100 km below the rift, whereas the heat flow anomaly must be caused by shallower sources in the lower crust or upper mantle. The new heat flow data therefore imply significant refinement of the deep temperature and electrical conductivity structures inferred from geomagnetic deep sounding, if it is assumed that the geothermal and transient magnetic studies are mapping the same high-temperature isotherms at depth.

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